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A REVIEW AND COMPARISON OF ALLOYS FOR FUTURE
SOLID-PROPELLANT ROCKET-MOTOR CASES

DEFENSE METALS INFORMATION CENTER
BATTELLE MEMORIAL INSTITUTE
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The Defense Metals Information Center was established at Battelle Memorial Institute at the request of the Office of the Director of Defense Research and Engineering to provide Government contractors and their suppliers technical assistance and information on titanium, beryllium, magnesium, aluminum, refractory metals, high-strength alloys for high-temperature service, corrosion- and oxidation-resistant coatings, and thermal-protection systems. Its functions, under the direction of the Office of the Director of Defense, are as follows:

1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

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FOREWORD

This memorandum is based on an informal report prepared in mid-1963 by the Defense Metals Information Center at the request of the U. S. Army. It is believed to be of sufficient interest to defense contractors and subcontractors working on materials for solid-propellant rocket motor cases that it was decided to distribute it to the DMIC audience. The preparation of the memorandum was the joint effort of a number of Battelle staff members. Major contributors were F. J. Barone, W. T. Black, J. E. Campbell, A. R. Elsea, V. W. Ellzey, A. M. Hall, W. S. Lyman, D. J. Maykuth, D. B. Roach, R. J. Runck, W. F. Simmons, and R. A. Wood.

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A REVIEW AND COMPARISON OF ALLOYS FOR FUTURE SOLID-PROPELLANT ROCKET-MOTOR CASES

SUMMARY

Metallic materials for solid-propellant rocket-motor cases in the period 1965-1970 probably will be confined to steel and alloys of titanium and aluminum. Of the three, titanium alloys have the greatest potential on the basis of usable strength-to-density ratio, followed by steel and aluminum alloys.

Of the potential steel alloys, by far the most of the current development work is being done on the 18 per cent nickel maraging steels. These steels have the promise of good fracture toughness at high strength levels, and perhaps most important, their heat treatment is favorable for the fabrication of very large boosters, compared to steels that must be austenitized after forming. Weldability of maraging steels has yet to be worked out, which should be possible in the next 5 years however.

Of steels that must be austenitized, quenched, and tempered, the modified silico-manganese steels, S5 tool steels, and AISI 9250 spring steel* have outstanding potential. These steels can be heat treated to very high strengths with good fracture toughness, compared to other low-alloy steels, and they can be welded reliably, although the properties of the weld metal are inferior to those of the base metal. At the same time, it is expected that some of the alloy steels, such as modifications of AISI 4340 steel and D6ac, that are being used today for certain smaller rocket-motor cases, will still be used in future motor case applications.

Titanium alloys continue to be relatively expensive, but they still have the greatest strength-to-density potential, and, in addition, possess outstanding resistance to corrosion. Development of new titanium alloys is being pursued at this time with the possibility of better titanium alloys being developed.

Except for Ti-6Al-4V, the titanium alloys that are candidates for rocket-motor cases present some problems in welding. There is a good prospect for improving this situation in the next 5 years, however. Welds with strengths comparable to that attainable in the base metal and acceptable notch toughness are unattainable at present in the Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn alloy.

Even though aluminum alloys are not now used in rocket motor case fabrication, newer alloys are being developed and tested, and may be feasible for such applications in the future.

INTRODUCTION

At the request of an agency of the U. S. Army, the Defense Metals Information Center prepared a brief review of metallic materials with potential for solid-propellant rocket-motor cases in the period 1965-1970. This memorandum is based on that review.

* An AISI 9200-series steel containing about 0.50 carbon.

Included are not only the alloys now under development that may be used during this time period, but also some presently used alloys that may continue to be used during this time period. Included also were some alloy systems that probably could be developed for this application.

This memorandum consists of three sections and an appendix. In the three sections, the current outlooks for steels, titanium alloys, and aluminum alloys as rocket-motor-case materials in the time period of interest – 1965-1970 – are discussed. The appendix of the memorandum is a series of data sheets summarizing the properties of the major alloys considered in the previous discussions.

An evaluation of materials for composites, such as spiral-wrap structures, is not included in this memorandum.

STEELS FOR SOLID-PROPELLANT ROCKET-MOTOR CASES IN THE PERIOD 1965 to 1970

Ultrahigh-Strength Low-Alloy Steels

The low-alloy type of steel, which is capable of achieving ultrahigh-strength levels by quenching and tempering, is a major construction material for solid-fueled rocket-motor cases. This type of steel, represented by D6ac, AISI 4340, and AMS 6434,* performs satisfactorily in such missiles as the Polaris, Nike, and Minuteman.

These steels are used regularly in the form of sheet some 0.070 to 0.110 inch thick at yield strengths in the range of 180,000 to 210,000 psi, and can be used at yield strengths up to about 220,000 psi. It is possible to heat treat the ultrahigh-strength low-alloy steels to considerably higher strength levels, up to 275,000-psi yield strength and higher. However, in most instances, the fracture strength of the steel, when in the form of relatively thin sheet and in the presence of the kinds of defects occurring in rocket-motor cases, decreases rapidly from a maximum of 210,000 to 220,000 psi, as the steel is heat treated to yield strengths above the 210,000 to 220,000-psi level. Therefore, because of this notch sensitivity versus yield strength relationship, most of the hardenable low-alloy steels cannot be used with confidence in solid-fueled rocket-motor cases at yield strengths above 220,000 psi.

The ultrahigh-strength low-alloy steels have been in existence for many years. Those that are used in missile applications either have a long history of production and usage in numerous applications calling for exceptional strength, or are modifications of such well-understood hardenable steels. These steels are available in a wide variety of forms including forgings, billets, structural shapes, bar stock, sheet, strips, plate, tubing, and wire. When consumable-electrode vacuum-arc remelted, or when vacuum-induction melted, these steels display greater notch toughness in the form of sheet, especially in the transverse direction, than do the same alloys when air melted. Acceptable procedures for brazing and welding the steels have been developed, and joint efficiencies in the order of 100 per cent are readily obtainable when optimum preheat,

* Data sheets giving the composition and properties of these steels and of all other alloys mentioned in the report appear in the Appendix to this memorandum.

postheat, and postweld heat-treating practices are used. These steels can be roll-formed, hydrospun, deep drawn, stretch formed, forged, and machined successfully when put in the appropriate condition (usually the annealed condition).

Such low-alloy hardenable steels as D6ac, AISI 4340, and AMS 6434 will continue to find extensive use in thin-walled solid-propellant rocket-motor cases for years to come. With steady improvement in the quality of mill products (chiefly control of decarburization and reduction in the size of stress-raising defects) and with refinements in fabrication and welding practices, these steels may be used at somewhat higher yield strengths than currently employed. Perhaps the level of 240,000-psi yield strength will be reached. Much depends on the improvement of nondestructive inspection techniques; the smaller the harmful defect which can be detected and removed, the higher the strength level at which the steel can be used with confidence.

The fracture toughness of these steels in section thickness of 1/2 and 3/4 inch, as now contemplated for larger boosters, is not well known. In any event, because cases made of these steels must now be quenched and tempered after fabrication and assembly, and because of the size limitations of present heat-treating facilities, these steels will not be used in large boosters unless substantial developments occur in metals-joining technology. If components and subassemblies could be fabricated into completed structures by some joining method which required only local heat treatment, or heat treatment of the entire structure at only moderate temperatures, to develop acceptable mechanical properties in the joints, then the ultrahigh-strength low-alloy steels would be candidates for large booster cases. Brazing or narrow-gap welding may be such a joining method.

Silico-Manganese Steels

Recent research indicates that the fracture strength of ultrastrong steels in the presence of stress-raising notches and defects is sensitive to variations in the alloy composition. The results thus far obtained show that modified medium-carbon silico-manganese steels, somewhat similar to AISI S5 (a shock-resisting tool steel grade) and AISI 9250 (a 9200-series steel containing about 0.50 carbon), have considerably greater fracture toughness than does the AISI 4340 or AMS 6434 type of steel. In the form of 0.070-inch-thick sheet, the silico-manganese steel has shown a fracture strength-to-yield strength ratio of unity at a smooth-bar yield strength of 260,000 psi, using a sheet-tensile specimen with a center fatigue crack 2t long. With the same center-notched sheet-tensile specimen, a one-to-one fracture strength-to-yield strength ratio could not be maintained in AISI 4340 at yield strengths above about 220,000 psi.

The medium-carbon silico-manganese steels are standard steels, frequently used for leaf springs and for cold-working tools and dies. The modifications which have been made in the composition of this type steel, which provide improvement in fracture strength, should cause no unusual problems in melting, rolling, fabrication, or welding. With a moderate amount of additional developmental effort, a modified S5 or AISI 9250 type of steel superior to other low-alloy quench-hardenable steels in fracture toughness, when in sheet form, could become a commercial reality in a short time. It is estimated that a time period of 2 or 3 years is required. Such a development could extend the useful strength level of the ultrastrong low-alloy steels for use in solid-fueled rocket-motor cases, in the form of sheet, to the 250,000 to 260,000-psi yield-strength level.

The same limitations which apply to the other low-alloy hardenable steels, regarding their use in the form of plate in large boosters, would also apply to the silicomanganese type of steel. At present, 100 per cent joint efficiency requires full heat treatment (i.e., quenching and tempering) after assembly.

It should be added that the work to date on the influence of composition, particularly alloy content, on the fracture toughness of low-alloy steels has indicated that further significant gains are possible. It is reasonable to expect that one or more preferred compositions could be developed with outstanding fracture toughness not only when used as sheet, but also as plate. Perhaps, within 3 or 4 years, a medium-carbon low-alloy steel could emerge which could be used with confidence in motor cases in the form of sheet at yield strengths up to 280,000 psi.

The Maraging Steels

The low-carbon high-nickel alloys which have come to be known as maraging steels have characteristics of great interest for rocket-motor-case applications. First, maraging steel sheet and plate (up to 1 inch) display a high degree of fracture toughness at yield strengths up to, and somewhat beyond, 250,000 psi. In addition, the thermal treatments for these steels, especially the 18Ni variety, are quite simple. A reasonably ductile martensite of moderate strength which can be worked and formed by numerous methods is obtained after annealing at 1500 F. Moreover, the formation of this structure is relatively insensitive to cooling rate. Ultrahigh strength is then achieved by a simple aging treatment in the vicinity of 900 F. Several welding methods have been developed for these steels. High strength can be achieved in a structure by welding annealed material (martensitic) and then aging directly afterwards, without including a postweld reannealing step. Capability to attain great strength by treatment and a moderate temperature after forming or joining means reduction of distortion and dimensional-change problems which plague conventional quench-and-temper operations. Of far greater importance in building big boosters, this heat-treating capability means that construction of ultrahigh-strength structures too large to fit in existing quenching furnaces is feasible. The possibility of being able to strengthen a huge maraging steel structure by heating it to 900 F and then cooling it in air, or in the furnace, is much more attractive than the alternative of having to heat treat a low-alloy hardenable steel structure by raising it to an austenitizing temperature and then quenching it.

Thus, the maraging steels are the outstanding choice today for big boosters. During the coming 2 years, several large boosters with diameters from 120 to 260 inches are scheduled to be constructed of the 18Ni variety of maraging steel. The yield-strength target will be in the range of 220,000 to 240,000 psi, and the material will be plate with thicknesses of 3/8 to 3/4 inch. Furthermore, it is quite possible that the maximum yield strength for reliable performance in missile cases can be increased to the 260,000 to 270,000-psi level in plate by further research and development effort.

HP 9-4-45

A relatively new steel, ready for commercial production, carries the trade designation of HP 9-4-45. This steel is of medium-carbon content and contains 9 per cent nickel and 4 per cent cobalt. This alloy is conventionally fabricated and heat treated,

and can be hardened to yield strengths in the range of 265,000 psi. At such yield strengths it is reported to have good fracture toughness when in the form of sheet. To develop ultrahigh strength in welded joints, the material must be given a full quenching and tempering treatment after welding. HP 9-4-45 is clearly a strong candidate for high-performance rocket-motor cases constructed from sheet metal.

Other Approaches

Ultrahigh strength can be achieved in metallic materials and metallic structures by means other than quenching and tempering, or solution annealing and aging. Among these other approaches known to develop high strength in steels are the following:

(1) Working of alloy steels in the metastable austenitic condition (hot-cold working)

(2) Cryogenic forming of austenitic stainless steels

(3) Cold expansion of structures made of certain high-ductility steels

(4) Bainitic steels.

Considerable experimental work is being done on the working of alloy steels in the metastable austenitic condition, especially at temperatures corresponding to the bay in the austenite transformation diagram — the steel having first been austenitized and then cooled to the working temperature. Yield strengths of 325,000 to 350,000 psi and above are attainable. Fracture-toughness characteristics although not yet well established, appear to be favorable. The steels investigated include H11, D6ac, AISI 4340, 300M, and AM 355. Hot-cold working looks like a promising method of developing extra strength in special components. By its nature, however, the process does not seem easily adaptable to large thin-walled structures with a high surface area-to-volume ratio where temperature control might be difficult.

Forming of such stainless steels as AISI 301 at cryogenic temperatures shows promise for developing extra-high strength in a structure. Subsize rocket cases, 12 inches in diameter, have been expanded with liquid nitrogen at -320 F, and tensile strengths above 260,000 psi have been developed thereby. Good fracture toughness is said to have been obtained. It is understood, however, that final mechanical properties are quite sensitive to small variations in the composition of the steel.

Much remains to be learned about cryogenic forming and the deformation of metals at subambient temperatures. Different metals and alloys respond in different ways. A potentially fruitful approach would seem to be to develop alloys especially for cryogenic forming. If these alloys are in the face-centered cubic crystallographic system, it should be possible to achieve high degrees of fracture toughness at ultrahigh strength levels.

Exceptional ductility and toughness are achievable in high-manganese steels of the Hadfield type when modified by additions of nickel. When these steels are work hardened to yield strengths of 180,000 to 200,000 psi, they retain Charpy vee-notch toughness values of 40 ft-lb at -100 F. This is about twice the notched-bar toughness of other steels when quenched and tempered to the same strength level.

It is conceivable that rocket-motor cases, even big boosters, could be fabricated from such steels as these and then expanded appropriately to final size to develop the desired strength. Very high fracture toughness should be obtainable. And, of course, the procedure would have the advantage of being carried out at ambient temperatures.

Another possible approach to an ultrastrong material for big booster structures which require plate and cannot be austenitized and quenched feasibly after assembly, would be to develop a steel in which bainite forms on continuous cooling from elevated temperatures. Of course, the bainite must be of such composition and microstructure as to possess the desired strength and toughness. Some research along these lines is in progress.

The advantage of bainitic steels in large booster construction would be that no postweld heat treatment would be required. With parent metal and weld metal of the proper composition, bainite with the desired properties would form on cooling after welding. Another necessary condition is that the tempering occurring in the weld heat-affected zones of the parent metal must not be harmful.

Estimates

(1) At present, existing low-alloy hardenable steels are satisfactory for applications in rocket-motor cases at a yield strength of about 210,000 psi, in sheet thicknesses up to about 0.10 inch.

(2) Within the next 2 years (by 1965), the 18Ni maraging steel will be satisfactorily employed in motor cases at a yield strength of about 230,000 psi. This strength will be realized in both sheet and plate.

(3) By 1970, it is quite possible that improvements in the maraging steels, the modified silico-manganese steels, or the HP 9-4-45 type of steel will permit the application of steels in motor cases, at yield strengths in the range of 260,000 to 270,000 psi.

(4) To use steels at increased strength levels in motor cases will also require considerable development effort in welding and in nondestructive testing.

(5) In addition, it is conceivable that by 1970 cases with improved strength and reliability could be manufactured by cryogenic forming of austenitic materials or stretching of high-ductility extra-tough special steels. These manufacturing procedures are potential alternate approaches to the manufacture of boosters too large for existing heat-treating facilities. It is possible that cryogenically formed austenitic stainless steels will be useful up to a yield strength of 275,000 psi. Stretched or expanded steels with high ductility might be used in the form of plate at yield strengths up to 200,000 psi. Production of cases by deforming steel in the metastable austenite condition is also a long-range possibility.

Other alloys might be mentioned; some like Ti-4Al-3Mo-1V are very similar to Ti-6Al-4V but offer no special benefits which would offset the advantages of the considerable experience with Ti-6Al-4V which has accumulated over recent years. Also, Ti-4Al-3Mo-1V is not as weldable as the Ti-6Al-4V grade. Some laboratory results with high-aluminum alloys (8 to 10 per cent aluminum) have shown exceptional strength properties. In other research work, additional beta compositions are being developed which might become rocket-motor case candidate materials in the time period under consideration. Also, a good possibility exists for the development of a higher strength alloy of the Ti-6Al-6V-2Sn type as a result of the research now in progress.

Ti-6Al-4V

The Ti-6Al-4V alloy has been produced commercially since 1954. It is available commercially in a wide range of mill products and sizes, and its properties are consistently reproducible. Some difficulty attends welding the alloy, but methods have been developed which are suitable for the construction of rocket-motor cases. The alloy costs at least twice as much as specialty steels but is the least expensive of the three titanium alloys under discussion.

Variables of primary fabrication (forging and rolling) influence the final properties of the alloy. In general, it is desirable that the last 30 per cent or so of reduction be given the alloy just below its beta transus temperature, for best properties. Deformation control is similarly important during fabrication of rocket-motor cases. Also, dimensions are held to within ± 10 per cent of the target shape to insure uniform working throughout the part.

A solution temperature high in the alpha-beta field gives the highest strength and maintains good ductility. Heat-treatment response varies with section size. A section 1 inch thick is about the maximum in which high strength can be attained. Transfer time from furnace to quench tanks should be as short as possible. Aging response should be determined using coupons from each rocket-case component. Heat-treatment response varies with each of the above variables and with oxygen content also.

In fabricating Minuteman motor cases, ring segments made by roll forging and end-closure forgings are rough machined, solution heat treated, final machined, partially aged during creep forming, and then circumferentially welded to form the motor case. Final aging is completed after welding. Fusion welding is accomplished using commercially pure filler wire under argon gas. Either TIG or MIG processes can be used to make the circumferential joints (which are the only type joints acceptable). Joint configuration and number of passes vary from company to company, but the joint sections are always reinforced to allow for the reduced strength in the joint caused by the alloy dilution with unalloyed filler metal. An undiluted joint prepared by using Ti-6Al-4V filler metal is possible but is not ductile enough for rocket-motor-case utility.

Ti-13V-11Cr-3Al

The Ti-13V-11Cr-3Al alloy is a metastable beta alloy, quite different from Ti-6Al-4V in both physical and mechanical characteristics. Having more than 25 per cent alloy content, the alloy structure is stabilized in the body-centered cubic form (beta)

down to 1275 F. With moderately rapid cooling, this structure is retained down to room temperature. In this condition, the alloy can be strengthened by reheating above 600 F where precipitation of the alpha phase (close-packed hexagonal structure) and of the compound $TiCr_2$ occurs. Cold or warm working of the metastable beta structure prior to aging enhances the mechanical properties. It is possible to form the alloy in the soft condition and then age to final properties after forming. The alloy has higher strength than Ti-6Al-4V in the aged condition. The main reason it has not yet found application in rocket cases is lack of experience in forming and heat treating, and problems in welding. Experimental cases have been produced by shear forming, by spiral wrapping, and by rolling and welding. The continuing research in manufacturing full-scale components, cylinders by shear forming and end closures by forging, appears to be the best approach.

The interrelation between fabrication, heat treatment, and properties for Ti-13V-11Cr-3Al is complex. In general, the best combinations of strength and ductility are obtained in heavily worked materials. Ideally, the working should include some amount of cold or warm working prior to heat treatment. Solution treating is usually done in the range 1400 to 1500 F. Aging is generally done at about 900 F. Extreme cold working (92 per cent) prior to aging has produced tensile strengths as high as 300,000 psi in small-section specimens.

The alloy can be fusion welded in the annealed condition with little difficulty when the usual techniques for titanium are used. Both similar and dissimilar weld metal compositions have been used. One of the problems in welding is the large grain size developed during the fusion process. Another is an apparent micro segregation of alloying constituents at weld-metal grain boundaries. These adversely affect the properties of the joint after aging. The ductility and toughness of aged weldments are generally low when large grains and grain-boundary precipitates are present. Completely satisfactory solutions to this problem are not at hand; but work continues.

Ti-6Al-6V-2Sn

The Ti-6Al-6V-2Sn alloy has been developed over the past few years under the sponsorship of the Watertown Arsenal Laboratories. In addition to the elements in its designation, it contains about 0.7 per cent iron and 0.7 per cent copper. The alloy is capable of yield strengths as high as 215,000 psi, while maintaining a few per cent of elongation and is readily formed and welded, although weldments require postweld heat treatment to restore ductility.

Ti-6Al-6V-2Sn responds to primary working and to heat treatment very like the Ti-6Al-4V alloy. Recommended solution-treating temperature is about 1650 F, and recommended aging temperature is about 1050 to 1100 F; lower aging temperatures give higher strength and lower ductility.

Unlike Ti-6Al-4V, the Ti-6Al-6V-2Sn has low ductility in the welded condition. Ductility can be restored to weldments by postweld heat treatments, although this treatment reduces the strength of the base metal. The eventual usefulness of this alloy in rocket-motor cases seems to be tied to the development of a postweld heat-treatment cycle that will render the weld ductile but not markedly decrease the heat-treated strength of the base metal. Such work is under way. One approach is to partially age prior to welding and then complete the aging during postweld heat treatment.

Estimates

(1) A titanium alloy is now available (Ti-6Al-4V) which can provide a rocket-motor case with a strength-to-density index of about 900,000, with good notch properties.

(2) By 1965, techniques will be available to produce rocket-motor cases of Ti-13V-11Cr-3Al which have strength-to-density indexes of about 1 million, and acceptable notch toughness. The cost of the Ti-13V-11Cr-3Al cases might be slightly greater than for Ti-6Al-4V cases of lower performance capability.

(3) By 1970, the producibility of Ti-6Al-4V rocket-motor cases will be far advanced. At the same time, cases capable of higher performance than Ti-6Al-4V cases will be attainable by using Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn alloys, possibly at a little higher cost.

ALUMINUM ALLOYS FOR SOLID-PROPELLANT ROCKET-MOTOR CASES FOR THE PERIOD 1965 TO 1970

Up to the present time, none of the solid-propellant rocket motors have had aluminum cases. However, aluminum must be considered in selecting materials for specific systems. Aluminum alloys in the annealed and solution-treated conditions are readily fabricated by the usual shop techniques for forming, machining, punching, etc. Personnel in the aerospace industry have gained experience over many years in these operations on aluminum alloys. Furthermore, many of the alloys are readily weldable and welded specimens of these alloys indicate relatively good weld efficiencies. In addition, the production capacity for aluminum alloy sheet and plate is sufficient to support an extensive rocket-case program if conditions should warrant.

Current commercial high-strength aluminum alloys do not have as high values for yield strength-density ratios as the ultrahigh-strength steels and titanium-base alloys. However, research on high-strength aluminum alloys is continuing. Much of this research is proprietary and the results are not generally available until development has reached the stage at which a final report is published or the alloy designation is registered with The Aluminum Association. The eight main aluminum alloy candidates for application in rocket-motor cases are listed and compared in Table 2. Additional data are given in the Appendix.

The major problem is not to achieve high strength alone but to achieve high strength with good fracture toughness and weldability (with good weld properties). The aluminum-copper-magnesium-manganese alloys, represented by Alloys 2014 and 2024 in the table, develop relatively high strengths after solution treating and aging heat treatments. However, in the solution-treated-and-aged condition these alloys have relatively low fracture toughness and welded specimens have substantially lower properties than specimens of the parent metal. The same is true for the higher strength aluminum-zinc-magnesium-copper alloys in the 7000 series, represented by Alloys 7079 and 7178 in the table. Alloy 2020-T6 also has relatively low fracture toughness. Experimental alloys have been developed with yield strengths over 100,000 psi but their fracture toughness and welding characteristics are not adequate for highly stressed pressure

TABLE 2. SUMMARY OF DATA ON ALUMINUM ALLOYS FOR ROCKET CASES

Alloys	Present Status	Usable Yield Strength-to-Density Ratio	Weld Properties[a]	Heat Treatment
Al-Cu-Mg-Mn (2014)	Commercial	590,000 (680,000)[b]	Poor	T6 (solution treat at 940 F + water quench + age at 340 F)
Al-Cu-Mn-Cd-Li (2020)	Commercial	790,000	Poor	T6 (solution treat + water quench + age)
Al-Cu-Mg-Mn (2024)	Commercial	470,000 (600,000)[b]	Poor	T4 (solution treat at 920 F + water quench + age at room temperature)
Al-Cu (2219)	Commercial	550,000	Good	T87 (age T37 material at 325 F)
Al-Zn-Mg (7039)	Commercial	610,000	Good	T6
Al-Zn-Mg-Cu (7079)	Commercial	690,000 (750,000)[b]	Poor	T6 (solution treat at 830 F + water quench + age at room temperature 5 days + age at 240 F for 48 hrs)
Al-Zn-Mg-Cu (7178)	Commercial	760,000 (870, 000)[b]	Poor	T6 (solution treat at 870 F + age at 250 F)
Al-Mg-Zn-Cu (X7002)	Experi-mental	590,000	Good	T6

(a) Relative comparisons based on appraisals in "Air Weapons Materials Application Handbook, Metals and Alloys", ARDC TR59-66, December, 1959, and "Standards for Aluminum Mill Products", The Aluminum Association, October, 1963.
(b) For extrusions.

vessels. Production of high-performance pressure vessels, such as rocket cases, requires material with sufficient fracture toughness to minimize occurrence of brittle fracture during proof testing. Brittle fracturing will tend to occur starting at small flaws during pressurizing before the stresses reach the yield strength, if the material does not have adequate toughness. These flaws may be of smaller sizes than can be detected by the usual nondestructive testing techniques.

The three alloys in Table 2 for which good weld properties are reported, Alloys 2219, 7039, and X7002, have lower strengths than the others but better toughness. They represent an attempt to optimize the combination of properties needed in motor cases. Other alloys of the Al-Zn-Mg type having improved properties are in the experimental category.

Pressure vessels have been made of alloys of the 2000 and 7000 series of alloys, and assembled with girth welds. The relatively low efficiency of the welds in these alloys was compensated for by having the weld lands thicker than the main portion of the shell. However, there are certain advantages to having a uniform thickness in the shell and weld lands. Consequently, research programs on aluminum alloy development are being directed toward obtaining alloys with good weld properties, and adequate toughness with high strength. For large cases, solution heat treating after welding is rather difficult so it is preferred that the welded case can be used as welded or after a postweld aging treatment. These aluminum alloys would not be satisfactory for cases that are exposed to elevated temperatures above their aging temperatures because their strengths decrease as the temperature is increased. For elevated-temperature service, the APM (aluminum powder metallurgy) alloy may be considered. The properties of APM Alloy XAP001 are given in the Appendix.

Several unconventional techniques have been presented for constructing rocket cases from aluminum alloys. Morales and Spuhler[1]* have suggested that for large boosters, a thick-walled tubular ingot could be ring rolled and roll extruded in the field to produce a cylindrical case that would be too large for overland transportation. The strengths of extruded alloys are higher than for rolled alloys as shown in Table 2 and in the data sheets in the Appendix. The same authors also suggested that a large booster case could be cast, assuming a finished wall thickness of about 1.5 inches. After finish machining, it could be given the standard T6 heat treatment for the alloy used.

Other investigators have suggested that a cylindrical case of aluminum alloy could be reinforced by wrapping it with high-strength steel wire, beryllium wire, or glass fiber. This would increase the hoop strength of the case so it could withstand higher internal pressures than could an unreinforced aluminum case. (In a cylindrical vessel, the tangential stresses are twice as great as the longitudinal stresses during pressurizing.) Development of filament-reinforced aluminum cases is discussed by Odel and Albert.[2]

Discussion

Table 3 lists the alloys or alloy groups and summarizes very briefly their relative strength, availability, and fabricability.

To evaluate the relative merits of materials listed in the table, the interrelationship of three factors must be recognized — tensile strength, weldability, and fracture toughness. Fracture toughness is the ability of a material to tolerate stress-raising flaws and defects when under high stress. This characteristic of materials is of concern because materials and structures cannot yet be made defect-free, nor can all defects be detected with current inspection methods. An increase in fracture toughness or weldability is usually gained at the expense of tensile strength. Heat treatment also is identified in the table because of its relationship to the application or system involved, i.e., the development of high strengths in steel by austenitizing and quenching poses practical problems in the fabrication of very large structures.

There are two ways of attacking the high-strength materials problem. The first is to search for materials that exhibit a given degree of fracture toughness at ever-increasing strength levels. This is the development of materials — the subject of this

*References appear at the end of the memorandum.

TABLE 3. SUMMARY OF INFORMATION ON ALLOYS WITH GOOD POTENTIAL FOR APPLICATION IN ROCKET-MOTOR CASES IN THE PERIOD 1965-1970

Alloy	Present Status	Yield Strength/ Density, in.	Weldability	Heat Treatment	Other Comments
		Steels			
Low Alloy Hardenable Quench and Tempered					
Modified 4340	Commercial alloy in production in rocket-motor cases	805,000	Variable, confirmed in production cases	Quench and temper after fabrication	
Modified S5 tool steels	Commercial alloy, but in research and development for rocket-motor cases	930,000	Good	Quench and temper after fabrication	
High Alloy Hardenable Quench and Tempered					
9Ni-4Co-0.45C	Commercial alloy, but in research and development for rocket-motor cases	930,000	Unknown	Quench and temper after fabrication	
Maraging					
18Ni (250)	Commercial alloy, but in research and development for rocket-motor cases	830,000	Not well established	Age after welding	
18Ni (300)	Under development	1,020,000	Not well established	Solution anneal; age after welding	
Worked Metastable Austenite	Experimental	1,250,000	Not weldable after working	Temper after working	Fracture toughness still uncertain
Cold-Worked Austenitic Stainless					
at Cryogenic Temperatures:					
Type 301 Stainless	Commercial alloy, but in research and development for rocket-motor cases	850,000	Good, weld before cold work	None	Corrosion resistant
at Room Temperature:					
PH Steels (AM 355)	Commercial alloy, but in research and development for rocket-motor cases	850,000	We'dable	None	Corrosion resistant; spiral-wrapped cases
Modified Hadfield	Experimental	880,000	Weld, then cold work	None	Not corrosion resistant
		Titanium Alloys			
Alpha Beta					
Ti-6Al-4V	Commercial alloy in production in rocket-motor cases	950,000	Good, confirmed in production cases	Solution treat, quench, and age	Corrosion resistant
Ti-6Al-6V-2Sn	Commercial alloy, but in research and development for rocket-motor cases	1,100,000	Postweld heat-treatment techniques must be developed	Solution treat, quench, and age	Corrosion resistant
Advanced Ti-6Al-6V-2Sn	Alloy development program in progress	1,250,000	Probably like the commercial Ti-6Al-6V-2Sn	Solution treat, quench, and age	Corrosion resistant

Table 3. (Continued)

Alloy	Present Status	Yield Strength/ Density, in.	Weldability	Heat Treatment	Other Comments
		Titanium Alloys (Continued)			
Beta					
Ti-13V-11Cr-3Al	Commercial alloy, but in research and development for rocket-motor cases	1,000,000	Acceptable, but welding problems remain to be solved	Solution treat, quench, and age	Corrosion resistant
Advanced Beta Alloy	Alloy development programs in progress	1,250,000	Probably like Ti-13V-11Cr-3Al	Solution treat, quench, and age	Corrosion resistant
		Aluminum Alloys			
Al-Cu-Mg-Mn (2014)	Commercial	590,000	Poor	Solution treat and age at 340 F (-T6)	
Al-Cu-Mg-Mn (2024)	Commercial	470,000	Poor	Solution treat and age at RT (-T4)	
Al-Cu (2219)	Commercial	550,000	Good	Age -T37 material at 325 F (-T87)	
Al-Zn-Mg (7039)	Commercial	610,000	Good	-T6 treatment	
Al-Zn-Mg-Cu (7079)	Commercial	690,000	Poor	Solution treat and age at room temperature and at 240 F (-T6)	
Al-Zn-Mg-Cu (7178)	Commercial	760,000	Poor	Solution treat and age at 250 F (-T6)	
Al-Mg-Zn-Cu (X7002)	Experimental	590,000	Good	-T6 treatment	

memorandum. The second method of attacking the problem is to search for means of improving processing, fabrication, and nondestructive testing so that less toughness is required.

By using all available methods strength levels of materials are increasing without loss in fracture toughness. As this has occurred, "toughness" requirements have been revised downward. It is inevitable that by 1970 materials now considered "too brittle" will be in use. The maximum flaw size that can not be inspected out and which may appear in the finished part determines the fracture toughness needed and the "usable" strength of a material.

The difficulties involved in making an adequate inspection of a large rocket-motor case should be appreciated. It has been stated[3] that the smallest crack that has been known to cause failure of a rocket-motor case was 1/32 inch long and 1/32 inch deep. This is a flaw small enough to be easily missed by most any production inspection method.

REFERENCES

(1) Morales, H. J., and Spuhler, E. H., "On Site Fabrication of a Large Aluminum Motor Case", Presented at the Solid Propellant Rocket Conference of the American Rocket Society in Philadelphia, Pennsylvania, January 30-February 1, 1963.

(2) Odel, C. H., and Albert, W. E., "The Filament-Reinforced Motor Case", Aerospace Engineering (April, 1962).

(3) Hendron, J. A., "Nondestructive Testing of High-Strength Steel Rocket Motor Cases", ASTM Fourth Pacific Area National Meeting, October 2, 1962.

APPENDIX

ALLOY DATA SHEETS

APPENDIX

ALLOY DATA SHEETS

Individual data sheets summarizing the comparative properties of each of the alloys discussed in the memorandum appear inthis Appendix in the following order:

Steels

Titanium Alloys

Aluminum Alloys

MATERIAL - Low-Alloy Steel	AISI 4340
NOMINAL COMPOSITION OR ANALYSIS	0.40C, 0.83Mn, 0.21Si, 0.72Cr, 1.77Ni, 0.26Mo, Fe

SMOOTH TENSILE PROPERTIES (75 F)*

	Tempered at: 350 F	500 F	700 F
Ultimate Tensile Strength, 1000 psi	--	--	--
0.2 Per Cent Offset Yield Strength, 1000 psi	220	204	187
Elongation, per cent	8	6	6
Reduction in Area, per cent	--	--	--
Direction of Specimen	T	T	T
Type of Specimen	Sheet, 0.080 inch thick		

*Austenitized at 1575 F/40 min; oil quench and temper 2 + 2 hr.

NOTCHED TENSILE PROPERTIES (75 F)*

	Tempered at: 350 F	500 F	700 F
Net Fracture Strength (Fnet), 1000 psi	239	228	215
Yield Strength, 1000 psi	220	204	187
Fnet/Yield Strength Ratio	1.08	1.12	1.15
Direction of Specimen	T	T	T
Type of Notched Specimen	3-inch-wide center-crack specimen, 0.080 inch thick (Srawley-type crack)		

*Austenitized at 1575 F/40 min; oil quench and temper 2 + 2 hr.

DENSITY, lb per cu in.	0.28		
YIELD STRENGTH/DENSITY RATIO	Temper: 350 F	500 F	700 F
	785,000	730,000	670,000

AVAILABLE FORMS	Any shape and size
SUPPLY SOURCES	Several
FABRICABILITY	Satisfactory processes established
WELDABILITY	Satisfactory processes established
SOURCE OF DATA	Aerojet-General (consumable-electrode vacuum-melted material)

MATERIAL - Low-Alloy Steel	D6A	
NOMINAL COMPOSITION OR ANALYSIS	0.42C, 0.79Mn, 0.27Si, 1.12Cr, 0.58Ni, 0.98Mo, Fe	

SMOOTH TENSILE PROPERTIES (75 F)*

	Tempered at:	
	400 F	1000 F
Ultimate Tensile Strength, 1000 psi	300	212
0.2 Per Cent Offset Yield Strength, 1000 psi	228	195
Elongation, per cent	8	9
Reduction in Area, per cent	--	--
Direction of Specimen	T	T
Type of Specimen	Sheet, 0.11 inch thick	

*Normalized 1650 F/40 min; austenitize 1550 F/1 hr; oil quench; temper 1 hr.

NOTCHED TENSILE PROPERTIES (75 F)*

	Tempered at:	
	400 F	1000 F
Net Fracture Strength (Fnet), 1000 psi	89	198
Yield Strength, 1000 psi	228	195
Fnet/Yield Strength Ratio	0.39	1.01
Direction of Specimen	T	T
Type of Notched Specimen	Sheet, 0.11 inch thick	

*Normalized 1650 F/40 min; hardened 1550 F/1 hr; oil quench; temper 1 hr.

DENSITY, lb per cu in.	0.28		
YIELD STRENGTH/DENSITY RATIO	Temper:	400 F	1000 F
		815,000	700,000
AVAILABLE FORMS	Any shape and size		
SUPPLY SOURCES	Several		
FABRICABILITY	Satisfactory processes established		
WELDABILITY	Satisfactory processes established		
SOURCE OF DATA	U. S. Naval Weapons		

MATERIAL - Low-Alloy Steel — AMS 6434

NOMINAL COMPOSITION OR ANALYSIS — 0.35C, 0.70Mn, 0.30Si, 0.80 Cr, 1.8Ni, 0.35Mo, 0.2V, Fe

SMOOTH TENSILE PROPERTIES (75 F)*

	Tempered at: 400 F	500 F	725 F
Ultimate Tensile Strength, 1000 psi	--	--	--
0.2 Per Cent Offset Yield Strength, 1000 psi	221	218	200
Elongation, per cent	--	--	--
Reduction in Area, per cent	--	--	--
Direction of Specimen	T	T	T
Type of Specimen	Sheet, 0.080 inch thick		

*Austenitized 1575 F/40 min; oil quench; temper 2 hr.

NOTCHED TENSILE PROPERTIES (75 F)*

	Tempered at: 400 F	500 F	725 F
Net Fracture Strength (Fnet), 1000 psi	247	232	231
Yield Strength, 1000 psi	221	218	200
Fnet/Yield Strength Ratio	1.12	1.06	1.15
Direction of Specimen	T	T	T
Type of Notched Specimen	3-inch-wide center-crack specimen, 0.080 inch thick (Srawley-type crack)		

*Austenitized 1575 F/40 min; oil quench; temper 2 hr.

DENSITY, lb per cu in. — 0.28

YIELD STRENGTH/DENSITY RATIO

Temper:	400 F	500 F	725 F
	790,000	780,000	715,000

AVAILABLE FORMS — Any shape and size

SUPPLY SOURCES — Several

FABRICABILITY — Satisfactory processes established

WELDABILITY — Satisfactory processes established

SOURCE OF DATA — Aerojet-General (consumable-electrode vacuum-melted material)

MATERIAL - Tool Steel	AISI S5 Tool Steel
NOMINAL COMPOSITION OR ANALYSIS	0.6C, 0.85Mn, 2Si, 0.25Cr, 0.25Mo, 0.20V, Fe
SMOOTH TENSILE PROPERTIES (75 F)*	600 F temper
Ultimate Tensile Strength, 1000 psi	333
0.2 Per Cent Offset Yield Strength, 1000 psi	294
Elongation, per cent	5
Reduction in Area, per cent	--
Direction of Specimen	L
Type of Specimen	Sheet, 0.062 inch thick

*Austenitized 1650 F; oil quench; temper 2 hr.

NOTCHED TENSILE PROPERTIES (75 F)	(Not well established)
DENSITY, lb per cu in.	0.28
YIELD STRENGTH/DENSITY RATIO	1,050,000
AVAILABLE FORMS	
SUPPLY SOURCES	1. Allegheny Ludlum 2. Crucible Steel
FABRICABILITY	(Not well established)
WELDABILITY	(Uncertain)
SOURCE OF DATA	Allegheny Ludlum

MATERIAL - Spring Steel	Modified AISI 9250
NOMINAL COMPOSITION	0.5C, 0.90Mn, 2.0Si, 0.1V, Bal Fe
SMOOTH TENSILE PROPERTIES (75 F)*	
Ultimate Tensile Strength, 1000 psi	259
0.2 Per Cent Offset Yield Strength, 1000 psi	246
Elongation, per cent	6
Reduction in Area, per cent	--
Direction of Specimen	L
Type of Specimen	Sheet, 0.050 inch thick

*Austenitized 1600 F; oil quenched; tempered 775

NOTCHED TENSILE PROPERTIES (75 F)	
Net Fracture Strength, 1000 psi	248 for 1T central fatigue crack
SOURCES	Not commercially available
FABRICABILITY	Probably good as annealed
WELDABILITY	Good as AISI 4340
SOURCE OF DATA	Battelle

MATERIAL - Manganese Steel	Modified Hadfield-Type Manganese Steel	
NOMINAL COMPOSITION OR ANALYSIS	0.95C, 13Mn, 5Ni, Fe	
SMOOTH TENSILE PROPERTIES (75 F)	Annealed	Cold Rolled, 40%
Ultimate Tensile Strength, 1000 psi	136.4	200.5
0.2 Per Cent Offset Yield Strength, 1000 psi	49.6	178.2
Elongation, per cent	99.0	35.0
Reduction in Area, per cent	50	47.5
Direction of Specimen	--	--
Type of Specimen	--	--
NOTCHED TENSILE PROPERTIES (75 F)	Annealed	Cold Rolled
Charpy; ft-lb (75 F)	161	51
(-100 F)	168	47
DENSITY, lb per cu in.	0.29	
YIELD STRENGTH/DENSITY RATIO	Annealed	Cold Rolled
	--	615,000
AVAILABLE FORMS	(Not commercially available)	
SUPPLY SOURCES		
FABRICABILITY	Very good	
WELDABILITY	No allotropic transformation; therefore near 100% weld efficiency expected	
SOURCE OF DATA	Paper by Manning & Martin entitled "Steels of Over 150,000 PSI Yield Strength of Interest for Deep-Submergence Hulls"	

MATERIAL - Nickel Steel	18Ni Maraging Steel	
NOMINAL COMPOSITION OR ANALYSIS	18Ni, 8Co, 5Mo, 0.4Ti, 0.1Al, 0.03C max., Fe	
SMOOTH TENSILE PROPERTIES (75 F)*	Aged 3 Hours at 900 F	
Ultimate Tensile Strength, 1000 psi	250-303	
0.2 Per Cent Offset Yield Strength, 1000 psi	240-296	
Elongation, per cent	11-10.5	
Reduction in Area, per cent	60-55	
Direction of Specimen	L	
Type of Specimen	1-inch bar	

*Solution anneal at 1500 F if desired; air cool.
Mars ~ing cycle: Hold 3 hr at 900 F; air cool.

NOTCHED TENSILE PROPERTIES (75 F)	50% Cold Worked; Aged	70% Cold Worked; Aged
Net Fracture Strength (Fnet), 1000 psi	--	--
Yield Strength, 1000 psi	300-309	326
Fnet/Yield Strength Ratio	>1	1.0
Direction of Specimen	--	--
Type of Notched Specimen	Kt>10	Kt>10
K_c, 1000 psi$\sqrt{in.}$	172-244	156
G_c, in-lb/sq in.	1100-1825	888

DENSITY, lb per cu in. — 0.289

YIELD STRENGTH/DENSITY RATIO — 830,000-1,020,000

AVAILABLE FORMS — Billet, plate, sheet

SUPPLY SOURCES

1. Allegheny Ludlum
2. Vanadium Alloy
3. Latrobe Steel
4. Republic Steel
5. U. S. Steel
6. Carpenter Steel
7. Bethlehem Steel
8. Lukens Steel

FABRICABILITY — (Expected good)

WELDABILITY — (Being established)

SOURCE OF DATA — INCO, Latrobe

MATERIAL - Low-Alloy Steel	HP 9-4-45		
NOMINAL COMPOSITION OR ANALYSIS	0.43C, 0.12Mn, 0.01Si, 8.50Ni, 0.30Cr, 0.07V, 3.75Co, 0.007P, 0.0075S, Fe		
SMOOTH TENSILE PROPERTIES (75 F)*	400 F Temper		
Ultimate Tensile Strength, 1000 psi	314	318	285
0.2 Per Cent Offset Yield Strength, 1000 psi	265	264	240
Elongation, per cent	11	7	6
Reduction in Area, per cent	39	22	--
Direction of Specimen	L	T	T
Type of Specimen	1/2" bar	1/2" bar	0.1" sheet

*Austenitize 1450-1500 F for 1/2 hr; oil quench; refrigerate at -120 F for 2 hr; temper 1 + 1 hr.

NOTCHED TENSILE PROPERTIES (75 F)	400 F Temper	
Net Fracture Strength (Fnet), 1000 psi	260	170
Yield Strength, 1000 psi	250	250
Fnet/Yield Strength Ratio	1.05	0.68
Direction of Specimen	2 x 8" sheet 0.08 inch thick Kt = 17	3 x 12" sheet 0.18 inch thick Kt = 17

DENSITY, lb per cu in.	0.28
YIELD STRENGTH/DENSITY RATIO	858,000-947,000
AVAILABLE FORMS	Plate, sheet, forgings
SUPPLY SOURCES	Republic Steel Corporation
FABRICABILITY	(Uncertain)
WELDABILITY	(Uncertain)
SOURCE OF DATA	Republic Steel Corporation (vacuum-melted, carbon-deoxidized material)

MATERIAL - Titanium Alloy — Ti-6Al-4V

NOMINAL COMPOSITION OR ANALYSIS — 6Al, 4V, 0.08C max, 0.03N max, 150 ppm H max, Ti

SMOOTH TENSILE PROPERTIES (75 F)*

	Annealed	Solution Treated, Aged
Ultimate Tensile Strength, 1000 psi	135.5	175.3
0.2 Per Cent Offset Yield Strength, 1000 psi	130.6	163.8
Elongation, per cent	12.8	6.4
Reduction in Area, per cent	--	--
Direction of Specimen	--	--
Type of Specimen	Sheet	

*Statistical averages from thousands of tests.

NOTCHED TENSILE PROPERTIES (75 F)

	Solution Treated, Aged
Net Fracture Strength (Fnet), 1000 psi	220
Yield Strength, 1000 psi	164
Fnet/Yield Strength Ratio	1.34
Direction of Specimen	--
Type of Notched Specimen	Kt = 10

DENSITY, lb per cu in. — 0.160

YIELD STRENGTH/DENSITY RATIO — 840,000 (annealed), 1,010,000 (aged)

AVAILABLE FORMS — Sheet, strip, plate, bar, billet, wire, extrusions, forgings

SUPPLY SOURCES

1. Bridgeport Brass
2. Crucible Steel
3. Harvey Aluminum
4. Republic Steel
5. Titanium Metals Corporation

FABRICABILITY — Annealed or solution treated; minimum bend radius 3-5t (RT)

WELDABILITY — Good; requires special techniques for reliable weld; use unalloyed or Ti-3Al filler metal for best results

SOURCE OF DATA — DMIC Memorandum 87, Metal Producers

MATERIAL - Titanium Alloys — Ti-13V-11Cr-3Al

NOMINAL COMPOSITION OR ANALYSIS — 13V, 11Cr, 3Al, 0.05C max, 0.08N max, 250 ppm H max, Ti

SMOOTH TENSILE PROPERTIES (75 F)

	Sheet		Forged Domes and Cylinders	
	(a)	(a)	(b)	(c)
Ultimate Tensile Strength, 1000 psi	206	208	140	204
0.2 Per Cent Offset Yield Strength, 1000 psi	188	192	128	189
Elongation, per cent	7	5	18	4
Reduction in Area, per cent	--	--	51	--
Direction of Specimen	L	T	--	--

Type of Specimen
- (a) Solution treated; aged at 900 F.
- (b) Forged; solution treated
- (c) Forged; solution treated; aged

NOTCHED TENSILE PROPERTIES (75 F)

	Sheet		Forged Domes and Cylinders	
	(a)	(a)	(b)	(c)
Net Fracture Strength (Fnet), 1000 psi.	--	--	204	220
Yield Strength, 1000 psi	--	--	128	189
Fnet/Yield Strength Ratio	--	--	1.59	1.16
Direction of Specimen	--	--	--	--
Type of Notched Specimen	Center-notched		Kt = 8	Kt = 3.9 bar.
K_c, 1000 psi $\sqrt{in.}$	72.5	50.0	--	--

(a), (b), (c) See footnotes above

DENSITY, lb per cu in. — 0.175

YIELD STRENGTH/DENSITY RATIO — 1,070,000-1,090,000

AVAILABLE FORMS — Sheet, strip, plate, bar, billet, wire

SUPPLY SOURCES
1. Bridgeport Brass
2. Crucible Steel
3. Republic Steel
4. Titanium Metals Corporation

FABRICABILITY — Solution treated; minimum bend radius of 2-4t (RT)

WELDABILITY — Excellent in annealed condition, but weld metal ages at different rate than base metal resulting in low joint efficiencies

SOURCE OF DATA — DMIC Report 110, Metal Producers

MATERIAL - Titanium Alloy	Ti-6Al-6V-2Sn
NOMINAL COMPOSITION OR ANALYSIS	6Al, 6V, 2Sn, 0.7Fe, 0.7Cu, 0.05C max, 0.04N max, 150 ppm H max, Ti

SMOOTH TENSILE PROPERTIES (75 F)

	Sheet				Forged Rings and Domes	
	(a)	(a)	(b)	(b)	(c)	(d)
Ultimate Tensile Strength, 1000 psi	152	157	218	218	200	144
0.2 Per Cent Offset Yield Strength, 1000 psi	144	150	211	211	182	132
Elongation, per cent	14	12	2	0.5	7	5
Reduction in Area, per cent	--	--	--	--	--	--
Direction of Specimen	L	T	L	T		

Type of Specimen
- (a) Annealed
- (b) Solution treated; aged 1050 F
- (c) Solution treated; aged 1000 F
- (d) Solution treated; welded; annealed 1400 F

NOTCHED PROPERTIES (75 F)

	0.1" Sheet		
	(e)	(f)	(g)
Net Fracture Strength (Fnet), 1000 psi	165	131	57
Yield Strength, 1000 psi	145	172	197
Fnet/Yield Strength Ratio	1.14	0.76	0.29
Direction of Specimen	L	L	L
Type of Notched Specimen	Machined center notch		
G_c, in-lb/in.^{2}	1211	664	157

- (e) Annealed; 1525 F - 1 hr - FC to 1300 F-AC
- (f) Solution treated and aged; 1625 F - 1/2 hr -WQ, 1200 F - 2 hr -AC
- (g) Solution treated and aged; 1625 F - 1/2 hr -WQ, 1050 F - 2 hr -AC

DENSITY, lb per cu in.	0.164
YIELD STRENGTH/DENSITY RATIO	810,000-1,290,000
AVAILABLE FORMS	Plate, bar, billet, wire, extrusions
SUPPLY SOURCES	1. Bridgeport Brass 2. Harvey Aluminum 3. Titanium Metals Corporation
FABRICABILITY	Annealed or solution treated; minimum bend radius 4-6t (RT) (Not fully established)
WELDABILITY	Good to marginal; requires postweld anneal which lowers strength of base metal
SOURCE OF DATA	DMIC documents, Metal Producers

MATERIAL - Aluminum Alloy	2014	
NOMINAL COMPOSITION OR ANALYSIS	0.8Si, 1.0Fe, 4.4Cu, 0.8Mn, 0.4Mg, 0.10Cr, 0.25Zn, 0.15Ti, Al	
SMOOTH TENSILE PROPERTIES (75 F)*	Plate	Extrusion
Ultimate Tensile Strength, 1000 psi	70	75
0.2 Per Cent Offset Yield Strength, 1000 psi	60	69
Elongation in 2 Inches, per cent	13	12
Reduction in Area, per cent	--	--
Direction of Specimen	T	L
Type of Specimen	1/2-inch D	1/2-inch D.
Hardness, Brinell (500-Kg Load)	135	--

*-T6, or -T651 treatments

NOTCHED TENSILE PROPERTIES (75 F)	(Not established)
DENSITY, lb per cu in.	0.101
YIELD STRENGTH/DENSITY RATIO	590,000 (plate), 680,000 (extrusion)
AVAILABLE FORMS	Sheet, plate, bar
SUPPLY SOURCES	1. ALCOA 2. Reynolds Metals Company 3. Kaiser Aluminum
FABRICABILITY	Satisfactory in -O temper
WELDABILITY	Weldable with special techniques
SOURCE OF DATA	The Aluminum Association

MATERIAL - Aluminum Alloy	2020
NOMINAL COMPOSITION OR ANALYSIS	4.5Cu, 0.5Mn, 0.20Cd, 1.3Li, Al
SMOOTH TENSILE PROPERTIES (75 F)*	Sheet
Ultimate Tensile Strength, 1000 psi	84
0.2 Per Cent Offset Yield Strength, 1000 psi	77
Elongation in 2 Inches, per cent	7
Reduction in Area, per cent	--
Direction of Specimen	--
Type of Specimen	1/2 inch wide

*-T6 treatment

NOTCHED TENSILE PROPERTIES	(Not established)
DENSITY, lb per cu in.	0.098
YIELD STRENGTH/DENSITY RATIO	790,000
AVAILABLE FORMS	Sheet
SUPPLY SOURCES	1. ALCOA 2. Reynolds Metals Company 3. Kaiser Aluminum
FABRICABILITY	Satisfactory in -O temper
WELDABILITY	Poor
SOURCE OF DATA	ALCOA

MATERIAL - Aluminum Alloy	2219
NOMINAL COMPOSITION OR ANALYSIS	0.2Si, 0.3Fe, 6.3Cu, 0.3Mn, 0.02Mg, 0.1Zn, 0.06Ti, 0.10V, 0.15Zr, Al

SMOOTH TENSILE PROPERTIES (75 F)*	Sheet
Ultimate Tensile Strength, 1000 psi	69
0.2 Per Cent Offset Yield Strength, 1000 psi	57
Elongation in 2 Inches, per cent	10
Reduction in Area, per cent	--
Direction of Specimen	T
Type of Specimen	1/2 inch wide
Hardness, Brinell (500-Kg Load)	128

*-T87 treatment

NOTCHED TENSILE PROPERTIES (75 F)	(Not established)
DENSITY, lb per cu in.	0.103
YIELD STRENGTH/DENSITY RATIO	550,000
AVAILABLE FORMS	Sheet, plate, bar, extrusions, forgings
SUPPLY SOURCES	1. ALCOA 2. Reynolds Metals Company 3. Kaiser Aluminum
FABRICABILITY	Good in T37 temper
WELDABILITY	Good in -T37 temper, 70% efficiency on biaxial loading, T87 postweld treatment, weld by inert-gas metal arc, use weld rod Type 2319
SOURCE OF DATA	The Aluminum Association

MATERIAL - Aluminum Alloy	7039	
NOMINAL COMPOSITION OR ANALYSIS	4.0Zn, 2.8Mg, 0.015Cu, 0.07Si, 0.10Ti, 0.15Fe, 0.3Mn, 0.2Cr, Al	
SMOOTH TENSILE PROPERTIES (75 F)*	Plate	0.063-Inch Sheet
Ultimate Tensile Strength, 1000 psi	68	63.0
0.2 Per Cent Offset Yield Strength, 1000 psi	60	54.2
Elongation in 2 Inches, per cent	12	11.0
Reduction in Area, per cent	--	--
Direction of Specimen	L, T	T
Type of Specimen	1/2-inch D.	1/2 inch wide

*-T6 treatment

NOTCHED TENSILE PROPERTIES (75 F)	Plate		0.063-Inch Sheet
	$K_t = 6.3$	$K_t = 13.0$	$K_t > 17$
Notched Strength, 1000 psi	94	73	60.2
Notched Strength-Yield Strength Ratio	1.5	1.2	1.1
Direction of Specimen	L, T	L, T	T

DENSITY, lb per cu in.	0.099	0.099
YIELD STRENGTH/DENSITY RATIO	610,000	550,000
AVAILABLE FORMS	Plate	

SUPPLY SOURCES

1. Kaiser Aluminum and Chemical Corporation
2. ALCOA

FABRICABILITY: Good

WELDABILITY: Good with X5039 rod

SOURCE OF DATA: Kaiser Aluminum and Chemical Corporation; ALCOA

MATERIAL - Aluminum Alloy	7079	
NOMINAL COMPOSITION OR ANALYSIS	0.3Si, 0.4Fe, 0.6Cu, 0.2Mn, 3.3Mg, 0.2Cr, 4.3Zn, 0.1Ti, Al	
SMOOTH TENSILE PROPERTIES (75 F)*	Plate	Extrusion
Ultimate Tensile Strength, 1000 psi	78	82
0.2 Per Cent Offset Yield Strength, 1000 psi	68	74
Elongation in 2 Inches, per cent	14	12
Reduction in Area, per cent	--	--
Direction of Specimen	T	L
Type of Specimen	1/2-inch D.	1/2-inch D.
Hardness, Brinell (500-Kg Load)	145	--

*-T6 or -T651 treatment

NOTCHED TENSILE PROPERTIES (75 F)	(Not established)
DENSITY, lb per cu in.	0.099
YIELD STRENGTH/DENSITY RATIO	690,000 (plate), 750,000 (extrusion)
AVAILABLE FORMS	Plate
SUPPLY SOURCES	1. ALCOA 2. Reynolds Metals Company 3. Kaiser Aluminum
FABRICABILITY	Good
WELDABILITY	Poor
SOURCE OF DATA	The Aluminum Association ALCOA

MATERIAL - Aluminum Alloy	7178	
NOMINAL COMPOSITION OR ANALYSIS	0.5Si, 0.7Fe, 2.0Cu, 0.3Mn, 2.7Mg, 0.3Cr, 6.8Zn, 0.2Ti, Al	
SMOOTH TENSILE PROPERTIES (75 F)*	Plate	Extrusion
Ultimate Tensile Strength, 1000 psi	88	96
0.2 Per Cent Offset Yield Strength, 1000 psi	78	89
Elongation in 2 Inches, per cent	11	10
Reduction in Area, per cent	--	--
Direction of Specimen	T	L
Type of Specimen	1/2-inch D.	1/2-inch D.
Hardness, Brinell (500-Kg Load)	160	

*-T6 or -T651 treatment

NOTCHED TENSILE PROPERTIES (75 F)	(Not established)
DENSITY, lb per cu in.	0.102
YIELD STRENGTH/DENSITY RATIO	760,000 (plate), 870,000 (extrusion)
AVAILABLE FORMS	Sheet, bar, plate
SUPPLY SOURCES	1. ALCOA 2. Reynolds Metals Company 3. Kaiser Aluminum
FABRICABILITY	Good
WELDABILITY	Poor, -T6 postweld treatment, weld by inert-gas metal arc, use weld rod Type 5556
SOURCE OF DATA	ALCOA, The Aluminum Association

MATERIAL - Aluminum Alloy	XAP001 (APM, ALCOA)
NOMINAL COMPOSITION OR ANALYSIS	6 per cent Al_2O_3 (For elevated temperature applications)
SMOOTH TENSILE PROPERTIES (75 F)*	Extrusion
Ultimate Tensile Strength, 1000 psi	37
0.2 Per Cent Offset Yield Strength, 1000 psi	27
Elongation in 2 Inches, per cent	13
Reduction in Area, per cent	--
Direction of Specimen	L
Type of Specimen	--
Yield Strength at 900 F, 1000 psi	10

*No thermal treatment

NOTCHED TENSILE PROPERTIES	(Not established)
DENSITY, lb per cu in.	0.099
YIELD STRENGTH/DENSITY RATIO	270,000 (101,000 at 900 F)
AVAILABLE FORMS	Alloy has been produced as sheet and plate
SUPPLY SOURCE	ALCOA
FABRICABILITY	Good
WELDABILITY	By special processes only
SOURCE OF DATA	ALCOA

MATERIAL - Aluminum Alloy	X7002 (Experimental)	
NOMINAL COMPOSITION OR ANALYSIS	3.35Zn, 2.0Mg, 0.88Cu, 0.04Si, 0.05Ti, 0.13Fe, 0.14Mn, 0.15Cr, Al	
SMOOTH TENSILE PROPERTIES (75 F)*	1-1/4-Inch Plate	0.063-Inch Sheet
Ultimate Tensile Strength, 1000 psi	70	69.3
0.2 Per Cent Offset Yield Strength, 1000 psi	60	59.6
Elongation in 2 Inches, per cent	12	10.8
Reduction in Area, per cent	--	--
Direction of Specimen	--	T
Type of Specimen	1/2-inch D.	1/2 inch wide

*-T6 treatment

NOTCHED TENSILE PROPERTIES (75 F)	0.063-Inch Sheet
Notched Strength ($K_t \geq 17$), 1000 psi	65.1
Notched Strength/Yield Strength Ratio	1.09
Direction of Specimen	T
DENSITY, lb per cu in.	0.102
YIELD STRENGTH/DENSITY RATIO	590,000
AVAILABLE FORMS	
SUPPLY SOURCES	1. Reynolds Metals Company 2. ALCOA
FABRICABILITY	Good
WELDABILITY	86% efficiency in tensile test, postweld age to T6 temper for plate
SOURCE OF DATA	Reynolds Metals Company ALCOA

MATERIAL - Aluminum Alloy	X7005 (Experimental)
NOMINAL COMPOSITION OR ANALYSIS	0.09Si, 0.13Fe, 0.10Cu, 0.52Mn, 0.99Mg, 0.12Cr, 4.42Zn, 0.03Ti, Al
SMOOTH TENSILE PROPERTIES (75 F)*	0.063-Inch Sheet
Ultimate Tensile Strength, 1000 psi	52.2
0.2 Per Cent Offset Yield Strength, 1000 psi	44.8
Elongation in 2 Inches, per cent	11.8
Reduction in Area, per cent	--
Direction of Specimen	T
Type of Specimen	1/2 inch wide

*-T6 treatment

NOTCHED TENSILE PROPERTIES (75 F)	0.063-Inch Sheet
Notched Strength ($K_t \geqslant 17$), 1000 psi	52.2
Notched Strength/Yield Strength Ratio	1.17
Direction of Specimen	T
DENSITY, lb per cu in.	0.102
YIELD STRENGTH/DENSITY RATIO	440,000
AVAILABLE FORMS	Experimental only
SUPPLY SOURCES	None
FABRICABILITY	Similar to 7039
WELDABILITY	--
SOURCE OF DATA	ALCOA

A-23 and A-24

MATERIAL	X7006 (Experimental)
NOMINAL COMPOSITION OR ANALYSIS	0.10Si, 0.17Fe, 0.04Cu, 0.22Mn, 2.24Mg, 0.12Cr, 4.10Zn, 0.01Ti, Al

SMOOTH TENSILE PROPERTIES (75 F)*	0.063-Inch Sheet
Ultimate Tensile Strength, 1000 psi	65.2
0.2 Per Cent Offset Yield Strength, 1000 psi	58.6
Elongation in 2 Inches, per cent	10.5
Reduction in Area, per cent	--
Direction of Specimen	T
Type of Specimen	1/2 inch wide

*-T6 treatment

NOTCHED TENSILE PROPERTIES (75 F)	0.063-Inch Sheet
Notched Strength ($K_t \geqslant 17$), 1000 psi	63.8
Notched Strength/Yield Strength Ratio	1.09
Direction of Specimen	T

DENSITY, lb per cu in.	0.102
YIELD STRENGTH/DENSITY RATIO	575,000
AVAILABLE FORMS	Experimental only
SUPPLY SOURCES	None
FABRICABILITY	Good (in T4 temper for welding)
WELDABILITY	Good, 90% efficiency in tensile test, postweld age to T6 temper, weld by inert-gas metal arc
SOURCE OF DATA	ALCOA

LIST OF DMIC MEMORANDA ISSUED
(Continued)

A list of DMIC Memoranda 1-164 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
165	Review of Uses for Depleted Uranium and Nonenergy Uses for Natural Uranium, February 1, 1963
166	Literature Survey on the Effect of Sonic and Ultrasonic Vibrations in Controlling Grain Size During Solidification of Steel Ingots and Weldments, May 15, 1963
167	Notes on Large-Size Furnaces for Heat Treating Metal Assemblies, May 24, 1963 (A Revision of DMIC Memo 63)
168	Some Observations on the Arc Melting of Tungsten, May 31, 1963
169	Weldability Studies of Three Commercial Columbium-Base Alloys, June 17, 1963
170	Creep of Columbium Alloys, June 24, 1963
171	A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys, July 15, 1963
172	Production Problems Associated with Coating Refractory Metal Hardware for Aerospace Vehicles, July 26, 1963
173	Reactivity of Titanium with Gaseous N_2O_4 Under Conditions of Tensile Rupture, August 1, 1963
174	Some Design Aspects of Fracture in Flat Sheet Specimens and Cylindrical Pressure Vessels, August 9, 1963
175	Consideration of Steels with Over 150,000 psi Yield Strength for Deep-Submergence Hulls, August 16, 1963
176	Preparation and Properties of Fiber-Reinforced Structural Materials, August 22, 1963
177	Designations of Alloys for Aircraft and Missiles, September 4, 1963
178	Some Observations on the Distribution of Stress in the Vicinity of a Crack in the Center of a Plate, September 18, 1963
179	Short-Time Tensile Properties of the Co-20Cr-15W-10Ni Cobalt-Base Alloy, September 27, 1963
180	The Problem of Hydrogen in Steel, October 1, 1963
181	Report on the Third Maraging Steel Project Review, October 7, 1963
182	The Current Status of the Welding of Maraging Steels, October 16, 1963
183	The Current Status and 1970 Potential for Selected Defense Metals, October 31, 1963